The University of Chicago
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The Relation Between P. D. and Spark-Length for Small Values of the Latter

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE OGDEN GRADUATE SCHOOL OF SCIENCE IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

(DEPARTMENT OF PHYSICS)

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[Plate XIII.]

I. *Introduction.*

THE general subject of spark-discharge in gases has commanded the attention of investigators for many years, but the recent developments of the electron theory have brought it into especial prominence within the last half-decade. The particular investigations on the spark-discharge between two electrodes and the potential necessary to produce discharge with varying distances have extended over a period of forty-five years, the first observations being made in 1860 by Lord Kelvin †. Since 1880, the field has been covered more rapidly and important investigations have been made by Baille ‡, Liebig §, Paschen ‖, Peace ¶, Strutt **, Bouty ††, Earhart ‡‡, and Carr §§. During this period the general behaviour of the discharge between electrodes throughout

† Lord Kelvin, "Collected Papers on Electrostatics and Magnetism," p. 247.

‡ Baille, *Annales de Chimie et de Physique* [5] xxv. p. 486 (1882).

§ Liebig, Phil. Mag. [5] xxiv. p. 106 (1887).

‖ Paschen, Wied. *Ann.* xxxvii. p. 79 (1889).

¶ Peace, Proc. Roy. Soc. lii. p. 99 (1892).

** Strutt, Phil. Trans. cxciii. p. 377 (1900).

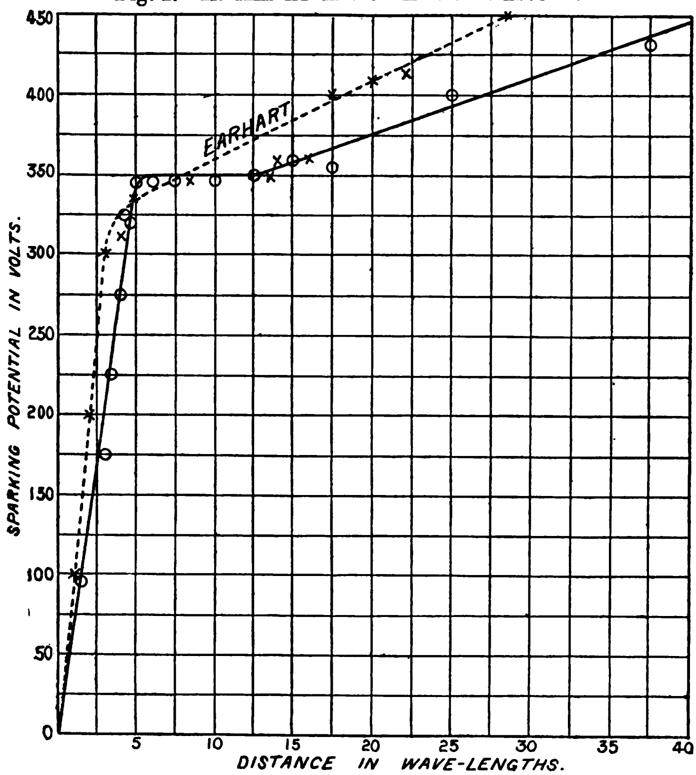
†† Bouty, *Comptes Rendus,* cxxxi. pp. 469, 503 (1900).

‡‡ Earhart, Phil. Mag. [6] i. p. 147 (1901).

§§ Carr, Proc. Roy. Soc. lxxi. p. 374 (1903).

large ranges of pressures and distance was investigated, and several important laws discovered. The linear relation between spark-potential and distance for comparatively large values of the latter was established, and Peace noticed the existence of a minimum spark-potential. Paschen deduced from a large number of observations the law which bears his name, viz., that for given potential-differences the product of the sparking distance and the maximum pressure for producing a spark is a constant. However, it was not until 1900 that any work was done to prove the correctness of these laws for very small distances. At this time, Earhart carried on an investigation in this laboratory in which, by the aid of the interferometer, he was enabled to make accurate observations down to the point of contact. His results were very interesting and, when plotted with potentials

Fig. 1.—In Air at Atmospheric Pressure.



as ordinates and sparking distances as abscissæ, gave in air at atmospheric pressure a straight-line curve (see fig. 1)

down to a distance of 3μ and a potential of 350 volts. At this point, the curve made a sharp bend and dropped in a straight line to the origin. Earhart also made observations in air at pressures of 228, 152, 40, and 15 cm., and in carbon dioxide at atmospheric pressure.

This investigation was begun in 1902, (1) in order to discover why Earhart's results did not show the minimum which Peace had observed; (2) to ascertain whether or not the material of the electrodes affected the position of the "elbow," as it might be expected to do if the metallic ions took part in the discharge at very small distances; (3) to extend the range of pressures much lower at these small distances than Earhart had done. Since this investigation was begun, there has appeared a paper by Carr * which covers in an admirable manner the third point mentioned above, but leaves the other two points untouched.

It would appear from the following results:—

(1) That the shape of the curve which is obtained with spherical electrodes is indeed precisely what is expected if there is a minimum spark-potential for flat electrodes.

(2) That the material of which the electrodes are composed exerts an important influence upon the spark-potential at small distances.

(3) That the carriers of the discharge for small distances come from the metal and not from the gas.

II. *Description of Apparatus.*

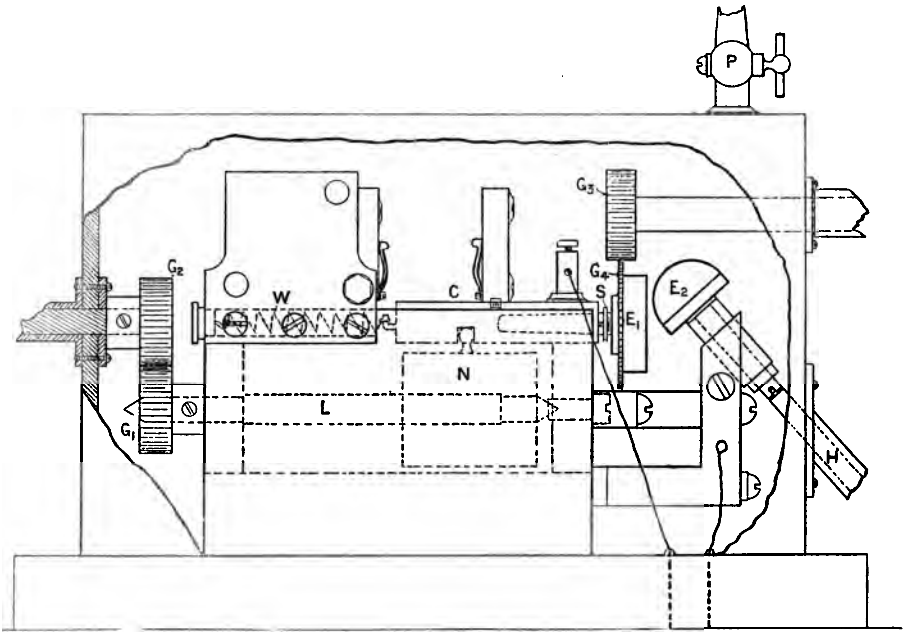
The apparatus, which is shown in fig. 2, consisted of an ordinary interferometer to which the two electrodes were attached. To obviate the necessity of using a tangent-screw and still maintain a sufficient accuracy of setting, the main screw of the interferometer was cut with a fifth-millimetre pitch which made it possible to control variations of a tenth of a fringe (*i. e.* $0{\cdot}025\,\mu$).

The movable carriage (C) of the interferometer supported the plane electrode (E_1), a disk of brass about 1 inch in diameter screwed tightly to a taper shaft which was set in a carefully-ground socket in the carriage and held in place by a spring (S). A thin gear (G_4) $1\frac{1}{2}$ inch in diameter was also concentric on the same shaft and, when engaged in the gear (G_3) above it which was operated outside of the box, could be turned on its axis. In order to get rid of the troublesome backlash in the nut (N), to which the sliding-carriage was fastened, a stiff coiled spring (W) running

* Carr, Proc. Roy. Soc. lxxi. p. 374.

parallel with the screw was attached to the carriage and the latter held in place upon the ways by three spring-clips. This device obviated all drifting contact and made the zero setting very definite.

Fig. 2.

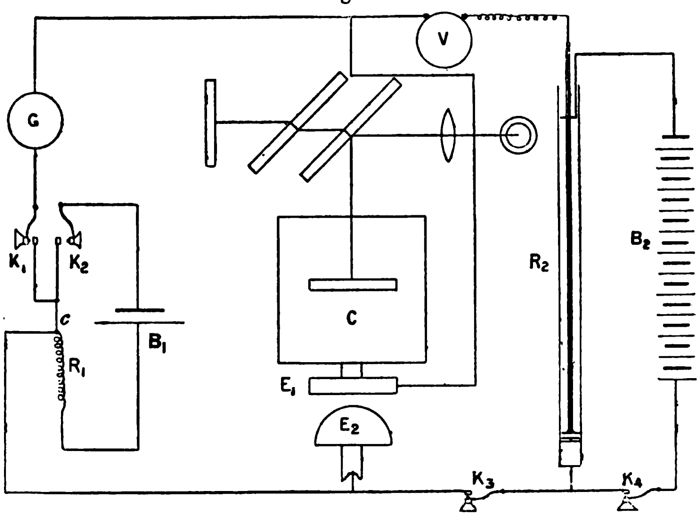


It was found necessary, in order to avoid vibration and similar effects, to attach the support of the spherical electrode to the interferometer-bed itself, insulating it of course so that the circuit would be complete only by the contact of the surfaces. This electrode was also screwed on a taper shaft which turned in a perfectly-ground sleeve, so set that the surface could be rotated on its axis at an angle of 45 degrees from the outside of the box. It is easily seen that by this arrangement the points of contact of both surfaces could be shifted after each discharge, and fifteen or twenty discharges taken before removing the box. This box was made of brass and carried on its sides the shafts of the two gears (G_2 and G_3) by which the rotation of the plane electrode and the main screw (L) of the interferometer was effected. It also carried a socket through which the shaft (H) for turning the spherical surface could be run after the box had been sealed. The joints of the three shafts were made air-tight by pieces of rubber tubing which allowed sufficient rotation for the

necessary adjustments. The box was connected to an air-pump through the stopcock (P), and after sealing the lower edges with bees-wax any desired pressure could be obtained.

A plan of the battery and galvanometer circuits, together with the arrangement of the interferometer mirrors, is shown in fig. 3. The potential was furnished by a battery of about five hundred storage-cells, and the sparking-potential was observed by a direct-reading voltmeter properly standardized.

Fig. 3.



The practice during an experiment was as follows :—The surfaces were carefully polished with very fine emery and rouge, set in position and the fringes adjusted in sodium light. A small quantity of drying substance was placed inside and the box sealed on. The air was pumped out and slowly let in again through a series of drying bottles, and the apparatus allowed to stand for a period of 6 to 24 hours. On beginning the observations, the surfaces were brought into contact by means of the interferometer-screw, the point of contact being shown by the deflexion of a sensitive galvanometer (G, fig. 3) when the spring-keys K_1 and K_2 were pressed. To avoid any possibility of the potential in this circuit effecting a discharge which would tarnish the surfaces, an ordinary dry cell (B_1) was connected to a german-silver resistance-coil (R_1) and a bit of copper wire (c) in series, and the fall of potential across this copper wire was the P.D. applied to the points between which the

discharge was to take place (about 0·01 volt)*. When contact had been established, the reading of the reference point was taken, and the surfaces drawn apart until the required number of fringes had passed the fiducial point. The main discharge circuit was then closed through the switches K_3 and K_4 and the plunger in the water resistance (R_2) raised very slowly until the potential of discharge was reached. In the neighbourhood of the discharge potential the P.D. was raised a volt at a time with a wait of a minute between in order that the effect of lag, first noticed by Warburg †, might be eliminated. The discharge was always indicated by the dropping of the pointer of the voltmeter. The electrodes were then drawn apart and fresh surfaces presented for contact by turning G_3 and H, and after a wait of 8 or 10 minutes to allow the gas to resume its normal condition another discharge was taken. The same pressure was maintained throughout each series of observations.

III. *Results in Air with Brass Electrodes.*

(1) *Comparison of Curve for Atmospheric Pressure with Earhart's Curve.*—The results with brass electrodes at various pressures are given in Table I., and represented graphically in fig. 4 (Pl. XIII.). In order to make comparisons the more easily, the curve for atmospheric pressure has been plotted with that of Earhart, in fig. 1, the latter being the dotted one. It will be seen that the discrepancy which exists at the "elbow" of the curve is really only apparent; for Earhart's results (indicated by ×) show a discharge-potential which is practically stationary at 348 volts for distances from 5λ to $13·5\lambda$. The difference in slope from the elbow to the origin in the two curves is shown by fig. 13 to be due to the metal of which the electrodes were composed, Earhart's surfaces being nickel. The agreement in the case of the curves for 40 and 15 cm. pressure is not so good, the errors in Earhart's observations being due probably to imperfect drying of the air.

* NOTE.—After the departure of the manuscript of this article, the attention of the writer was called to the fact that the indicating potential for different metals should not be below certain minimum values. This explained a difficulty experienced in obtaining definite contact between certain metals, a fact which is mentioned later in the article to explain rather scattered results for zinc, antimony, &c. These curves have been repeated, using a higher indicating potential, and much more consistent results have been obtained. The new results, together with observations on several metals not previously used, will be published in a subsequent article.

† Warburg, *Ann. d. Phys.* vol. lxii. p. 385.

TABLE I.—Brass Electrodes in Air. (Fig. 4, Pl. XIII.)

Pressure Atmospheric.		Pressure 40 cm.		Pressure 25 cm.		Pressure 15 cm.		Pressure 1 cm.	
Dist. in Wave-lgths.	Spark-Poten. in Volts.	Dist. in Wave-lgths.	Spark-Poten. in Volts.	Dist. in Wave-lgths.	Spark-Poten. in Volts.	Dist. in Wave-lgths.	Spark-Poten. in Volts.	Dist. in Wave-lgths.	Spark-Poten. in Volts.
1·5	95	2·0	110	2·5	165	2·0	225	3·0	240
3·0	175	2·0	175	3·0	160	3·0	210	3·0	270
3·5	225	2·5	190	3·0	170	4·0	285	4·0	345
4·0	275	3·0	150	3·0	175	4·5	345	4·5	345
4·2	325	3·2	265	4·0	305	5·0	340	5·0	350
4·5	320	4·0	305	5·0	340	7·5	340	7·5	350
5·0	345	4·5	335	7·5	340	10·0	350	15·0	350
6·0	345	4·7	345	10·0	345	12·5	350	25·0	350
7·5	345	5·0	355	12·5	345	17·5	350	50·0	350
10·0	345	6·0	317	17·5	345	25·0	350	75·0	350
12·5	350	7·5	340	25·0	350	37·5	350		
15·0	360	10·0	340	35·0	350	42·5	350		
17·5	355	10·0	350	37·5	355	50·0	350		
25·0	400	15·0	350	40·0	360	60·0	360		
37·5	430	17·5	350	40·0	370	65·0	375		
		20·0	350	40·0	370	75·0	410		
		22·5	350	42·5	390				
		22·5	345	50·0	390				
		25·0	365	67·5	430				
		27·5	365						
		37·5	375						
		37·5	395						
		50·0	415						
		50·0	420						

(2) *Minimum Spark-Potential for Curved Electrodes.*—According to Peace and Carr, at a given distance between the electrodes a discharge will take place at the minimum spark-potential (characteristic of the gas) if the pressure has a certain value called the "critical pressure." Now if either the distance or the pressure be decreased while the other is kept constant, it will be found necessary to increase the potential in order to produce a discharge. These facts were observed with the use of plane electrodes; but where one of the electrodes is spherical as in this case, it will be seen, as indeed Carr pointed out, that when the nearest point of the curved surface is closer to the flat electrode than the distance at which the discharge takes place with a potential equal to the minimum value, the spark can still pass at this potential from a point further out on the curved surface.

It will be seen therefore, that with such electrodes the discharge-potential, instead of passing through a minimum

should remain constant until the electrodes approach so near that the discharge is effected by the metal ions themselves. To take for example the case where the pressure of the gas was 15 cm., as the distance between the electrodes is decreased the sparking potential falls in a straight line to 350 volts, reaching this value when the sparking distance is $57\lambda\,(31{\cdot}6\,\mu)$. It then remains absolutely constant until the distance has reached $5\lambda\,(3\mu)$, when the potential drops rapidly to zero. An examination of the curve for 15 cm. pressure in fig. 4 will show that the results obtained are in perfect accord with this theory.

(3) *Effect of Change in Pressure on the Curves.*—It will be noticed that the curves for the various pressures reach the minimum potential at distances inversely proportional to the pressure. This agrees with Paschen's law which has been beautifully verified by Carr, who showed that for a given potential, *e.g.* the minimum potential, the discharge was only dependent upon the mass of the gas per unit surface between the electrodes. Taking Carr's value of 4·98 mm. for the critical pressure at 1 mm. distance, it is easy to calculate at what points the curves should reach the minimum potential for the various pressures. The following values were obtained:—

Spark-Potential.	Critical Pressure.	Distance in Wave-lengths, calculated.	Distance in Wave-lengths, observed.
350 kil.	75 cm.	13·2	12·5
350	40 „	25	26
350	25 „	40	35
350	15 „	66·6	58
350	1 „	1000	...

The discrepancies in the results for the lower pressures are undoubtedly due to the distortion produced in the field by the spherical electrode, a fact which would seem to indicate a limiting distance of 15μ, within which the field between the electrodes is practically uniform. The minimum spark-potential of 350 volts agrees with the value obtained by Carr and others.

Observations at lower potentials than 150 volts were seldom taken, for the reason that the portion of the curve from this point to the origin has been well explored in an investigation in this laboratory by Professor Kinsley* in connexion with a coherer problem, the apparatus used being susceptible of a higher order of accuracy at these minute distances.

* Kinsley, Phil. Mag. [6] vol. ix. p. 692 (1905).

IV. *Influence of the Kind of Metal in the Electrodes upon the Discharge.*

(1) *Observations in Air at Atmospheric Pressure with different Electrodes.*—In order to investigate the effects of the material of the electrodes upon the spark-potential, which was the primary object of the research, observations at atmospheric pressure similar to those above given for brass surfaces were taken with a series of electrodes of exactly the same size and shape but consisting of the following metals: aluminium, silver, bismuth, zinc, platinum, antimony, magnesium, nickel.

Considerable difficulty was experienced with the crystalline metals, antimony, bismuth, magnesium, and zinc, on account of uncertainty of contact. The results with these metals therefore show much more scattering observations than the others, and the slopes of the curves are consequently somewhat less reliable. The effect on the discharge is nevertheless so unmistakable that the general conclusion is unavoidable. The table and curve of each metal are given below with the exception of brass, which is found in Table I. and fig. 4 (Pl. XIII.). A first and second series of observations for each metal, representing readings taken on widely different days, are given in each table and shown separately on each curve.

Table II.—Aluminium. (Fig. 5, Pl. XIII.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
2	150	2	100
3	210	2·5	140
3	180	2·5	150
4	230	3	150
4	240	3·5	220
4·5	295	4	280
4·5	305	5	320
4·5	290	5·5	350
5	315	6	350
5	315		
6·2	335		
6·2	325		
7·5	335		
7·5	325		
10	345		
12·5	345		

TABLE III.—Silver. (Fig. 6.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
2	175	1	50
2·5	210	1·5	95
2·7	285	1·5	165
3·5	305	2	190
4	315	2·5	265
4·5	345	3	250
5	350	3	310
		3·5	340
		4	350

TABLE IV.—Bismuth. (Fig. 7.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
1·5	110	1·5	100
2·2	165	2	160
3	220	2·7	215
3·2	245	3·2	275
3·5	260	3·2	275
3·5	275	4·2	350
4·5	350	3·7	350

TABLE V.—Zinc. (Fig. 8.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
2	170	1·5	130
2	140	2	220
2	125	2	185
2·5	185	2·5	230
3	170	2·5	235
3	130	3	325
3	230	3	285
3	215	3·5	310
3·5	220	3·5	290
3·5	335	4	260
3·5	335	4·2	315
3·5	285	4·5	350
4	305	4·7	320
4	245	5	350
4·2	285		
4·2	310	4·5	350, 225, 350
4·2	315	5	350
4·2	350	6	350

TABLE VI.—Platinum. (Fig. 9.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
1	110	·9	90
1·5	180	1·5	150
1·5	185	2	350
2	225	2	230
2·2	250	2·5	260
2·5	310	3	350
2·5	280	3	350
2·7	260	4	350
3	280	8	350
3	350	10	350
4	350	12·5	350
		15	360
		25	400
		37·5	435

TABLE VII.—Antimony. (Fig. 10.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
2	115	1	110
2	245	1·5	185
2·5	270	1·5	125
2·5	250	1·7	285
3	240	2	350
3	220	2	160
3	320	2·5	350
3·5	350	2·5	175
3·5	350	2·5	180
4		3	350
		3	180
		4	350

TABLE VIII.—Magnesium. (Fig. 11.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
1·5	35	2	170
2	215	2·5	195
2·5	270	2·5	110
2·7	300	3	205
3	155	3·5	275
3·5	260	4	325
4	275	4	335
5	350		

TABLE IX.—Nickel. (Fig. 12.)

1st Series.		2nd Series.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
2	170	1·5	180
2·5	220	2	210
3	250	3·2	280
3·7	350	4	350
4	335	4·2	350
4·2	350	5	350
4·5	330		
5	350		
6	350		

(2) *Discharges at less than the Minimum Spark-Potentials carried by Metal Ions.*—If the discharges corresponding to the above curves from the elbow down are carried by the metal ions, it is to be expected that the nature of the electrode would have an effect upon the position of the elbow, for the force which holds the ions within the metals may be assumed to depend upon the nature of the metal. It will be seen that the above curves completely corroborate this inference. The potential begins to fall below the minimum value at the following distances:—

Aluminium	5·6 waves.
Brass	5
Bismuth	4·5
Magnesium	4·5
Zinc	4·5
Nickel	4·2
Silver	3·8
Antimony	3·5
Platinum	3

To illustrate this point the curves previously given are all collected in fig. 13 (Pl. XIII.). It will be observed that in all these cases the curves have been checked by two sets of observations taken at widely different times. With platinum, brass, and nickel, the observations are very definite and the points lie extremely close to the line. For these metals, therefore, the results are thoroughly trustworthy. In the case of the other metals the results are less definite, as the

tables show, but the slopes obtained by the two series of observations are nevertheless in good agreement.

Further evidence that the carriers of the discharge within the limits specified come from the metal and not from the gas, is found in the fact that the slope of the curve below the elbow is completely independent of the pressure of the gas, as is shown in fig. 4, and also independent of the nature of the gas, as shown in fig. 9.

Furthermore, the character of the discharge as observed in the behaviour of the voltmeter is completely different below the elbow from its character on that portion of the curve to the right of the elbow. When the discharge took place at or above the minimum spark-potential, the pointer of the voltmeter experienced a sudden deflexion of a number of divisions towards zero, and quickly returned to the old value as the potential was built up by the cells. On the other hand, when the discharge took place at points on the curve below the elbow, the pointer always fell completely to zero and remained there. Moreover, a test of the circuit with the galvanometer showed that coherence had taken place. That the coherence was not due to any give in the supports because of electrostatic attraction between the electrodes is definitely proved by the facts presented in figures 9 and 13, showing that the elbow varies with the nature of the electrode and with the nature of the gas. (This last result is discussed in the following section.)

(3) *Observations in Hydrogen and Carbon Dioxide at Atmospheric Pressure with Platinum Electrodes.*—In order to check still further the participation of the metal ions in the discharge at small distances, some observations were taken with platinum electrodes in an atmosphere of hydrogen and of carbon dioxide. The results are shown in Table X. and graphically in fig. 9 (Pl. XIII.).

The minimum spark-potentials for these gases are, according to Carr, respectively 280 and 420, while according to these results they are 285 and 420. Now if the metal ions are the carriers of the discharge for all potentials below the minimum value for the gas, then the curve in any gas should follow the slope found for air until the potential reaches the minimum value for the gas, when the curve should bend to the horizontal, *i. e.* the discharge should at this point begin to take place in the gas. This must be true, for if the curve should hold to the straight line beyond this point, the discharge would be produced by the metal ions at a higher potential than was necessary for discharge at the same distance in the gas itself. Taking Carr's values for the critical pressure for

TABLE X.—Platinum in H and CO_2.

Hydrogen.		Carbon dioxide.	
Distance, λ.	Potential, volts.	Distance, λ.	Potential, volts.
1·5	175	1·2	140
2	242	2	255
2·5	275	2·7	320
2·5	275	3·4	390
3	280	3·7	420
4	285	5	420
6	285	7·5	420
10	285	10	420
12·5	285	12·5	420
15	285	15	430
29	290	25	465
37·5	320	37·5	515
50	365		

hydrogen, 10·3 mm. at 1 mm. distance and 280 volts, and for CO_2, 5·03 mm. at the same distance and 420 volts, the calculations can be made for the distances at which the curves should rise above the minimum potential abscissæ. These calculations give 28 λ for hydrogen and 12·5 λ for CO_2, which agree almost exactly with the experimental values obtained (see fig. 9).

(4) The lag which is characteristic of the discharge at higher potentials disappears entirely for distances below the elbow.

V. *Summary.*

(1) With one spherical and one plane electrode, at constant pressure the spark-potential is directly proportional to the distances between the electrodes, until the potential reaches the minimum value for the gas.

(2) In any gas the potential of discharge reaches its minimum value for the gas at distances which are inversely proportional to the pressures existing between the electrodes.

(3) For the same electrodes the discharge in air at distances from zero to about 3μ is wholly independent of the pressure or of the nature of the gas between the electrodes.

(4) For the same electrodes the distances at which the curves assume a horizontal slope are proportional to the minimum spark-potential of the gas between the electrodes.

(5) When a discharge of electricity occurs between two

electrodes at a lower potential than the minimum spark-potential of the gas in which the discharge occurs, the discharge is produced wholly or in part by the metal ions.

In conclusion I desire to thank Professor Michelson for his kindly interest in my work and for several helpful suggestions.

I wish also to thank Professor Millikan for suggesting the problem and for his valuable counsel throughout this work. I can not adequately express my deep appreciation of his efforts in my behalf.

Ryerson Laboratory,
University of Chicago.
April 1905.

Phil. Mag. Ser. 6, Vol. 10, Pl. XIII.

ENT GASES.